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INFO-0243

DETECTION AND MITIGATION OF AGING AND SERVICE WEAR EFFECTS OF NUCLEAR POWER PLANT COMPONENTS IN CANADA

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July 1987

Canada

Paper

87-06486/

RÉSUMÉ

Au Canada, la gestion de la sûreté d'exploitation des centrales nucléaires utilise des méthodes qui visent à prévenir, détecter, rectifier et atténuer les défaillances des composants et des systèmes, quelle qu'en soit la cause, y compris la dégradation due au vieillissement ou à l'usure. Le présent document donne un aperçu de l'application de ces méthodes pour la détection et l'atténuation des effets de vieillissement avant qu'ils aient une incidence sur la sûreté des centrales et la fiabilité de la production. Il décrit aussi les audits réglementaires de ces méthodes, qui visent à assurer que les titulaires de permis des centrales nucléaires maintiennent un niveau de sûreté acceptable dans leurs centrales. Ces méthodes sont les suivantes : un programme d'entretien préventif, un système de notification des incidents graves, ainsi qu'une évaluation de la fiabilité du rendement des systèmes liés à la sûreté. Les méthodes susmentionnées sont discutées et illustrées par des exemples. Les résultats obtenus durant 163 années-réacteurs d'exploitation montrent que cette optique est valable. Cette optique, qui fait partie intégrante des principes canadiens en matière de sûreté des réacteurs, s'est améliorée continuellement depuis qu'elle a été adoptée en 1962. Les améliorations actuelles et futures comprennent des examens des méthodes actuelles de contrôle, d'essai et d'inspection pour s'assurer que sont vérifiés les paramètres appropriés qui varient avec le temps (qui peuvent révéler la dégradation par vieillisement avant que survienne une perte de capacité fonctionnelle), ainsi que des examens de l'efficacité des méthodes et des programmes d'entretien actuels pour atténuer les effets du vieillissement et de l'usure.

DETECTION AND MITIGATION OF AGING AND SERVICE WEAR EFFECTS OF NUCLEAR POWER PLANT COMPONENTS IN CANADA

Paper presented at the International Symposium on Safety Aspects of the Aging and Maintenance of Nuclear Power Plants, International Atomic Energy Agency, Vienna, Austria, June 29-July 3, 1987.

ABSTRACT

In Canada, the operational safety management of nuclear power plants employs methods which are intended to prevent, detect, correct and mitigate system and component failures from any cause, including the effects of aging and service wear degradation. The paper gives an overview of the application of these methods in the detection and mitigation of aging effects before they impact on plant safety and production reliability. Regulatory audits of these methods, to ensure that an acceptable level of plant safety is maintained by the nuclear power plant licensees, are also described. The methods are: a preventive maintenance program, Significant Event Reporting system, and a reliability based assessment of performance of safety related systems. The above methods are discussed and illustrated by examples. The soundness of the approach has been proven by the results achieved in 163 reactor-years of operation. The approach, which is an integral part of the Canadian reactor safety philosophy, has undergone continuous improvement since its inception in 1962. Present and future developments include reviews of current monitoring, testing and inspection methods to ensure that appropriate time variant parameters (capable of revealing aging degradation before loss of functional capability) are monitored, and reviews of the effectiveness of existing maintenance programs and methods in mitigating aging and service wear effects.

1. INTRODUCTION

The Canadian approach to managing aging (i.e., time dependent) degradation of nuclear power plant (NPP) components is an integral part of the overall Canadian approach to reactor safety. This approach does not depend on perfection of any safety measure but allows for design imperfections and occasional equipment failures and operator errors.

An important characteristic of the Canadian reactor safety philosophy is that primary responsibility for an NPP's safety is clearly on the licensee. The Canadian nuclear regulatory agency, the Atomic Energy Control Board (AECB), sets general performance requirements, accepts or rejects licensee's proposals to meet those requirements, and monitors a licensee's performance to ensure that the requirements are met.

The operational safety management program, developed by Ontario Hydro and accepted by AECB, employs methods intended to prevent, detect, correct, and mitigate system and component failures from any cause, including the effects of aging and service wear degradation. This paper concentrates on the use of the program to manage aging degradation of plant components. It is based on the experience of the AECB and Ontario Hydro, a utility with the largest and oldest nuclear power program in Canada. Table I shows the evolution of Canadian nuclear generating capacity. The other two Canadian utilities with nuclear power plants are using similar methods to detect and mitigate aging effects, based on the same reactor safety approach. Section 2 of the paper presents an overview of the application of these methods in the detection and mitigation of aging effects, Section 3 briefly describes regulatory audits of the methods, and Section 4 outlines the present and future developments.

2. MANAGING AGING DEGRADATION THROUGH THE OPERATIONAL SAFETY MANAGEMENT PROGRAM

The operational safety management program consists of a preventive maintenance program, the Significant Event Reporting (SER) system, and a reliability based assessment of performance of safety related systems. These methods were put in place at the beginning of the Canadian nuclear power program in the early 1960s with the objective of preventing, detecting, correcting, and mitigating failures of NPP systems and components from all possible causes. The effect of wear-out on equipment and system reliability was well recognized, and the intent has been to maintain plant systems and components in their "useful life" condition. All three methods mentioned above play an essential and complementary role in meeting this intent and achieving a high level of plant safety and production reliability.

In the context of this paper, the role of preventive maintenance, as the name implies, is to prevent failures through detection and mitigation of equipment degradation; the role of the SER system is to prevent future failures through operational, maintenance and design changes made on the basis of lessons learned from experienced failures or deficiencies; and the role of reliability assessment of safety related systems performance is to detect deteriorating performance to be able to initiate corrective actions before individual component failures impact on system reliability.

2.1 Preventive Maintenance Program

This section does not attempt to describe a preventive maintenance program, but aims to show an actual program development pertinent to managing of aging degradation.

TABLE I - EVOLUTION OF CANADIAN NUCLEAR GENERATING CAPACITY

Operator and Plant	Unit	Net MW(e)	In-service Year	Age	Comment
ONTARIO HYDRO					
NPD	Single	22	1962	25	Demonstration plant
Douglas Pt.	Single	206	1968	16	Decommissioned 1984
Pickering A	1	515	1971	16	Shut down 1983 to 1987 for pressure tube replacement
	2	515	1971	16	
	3	515	1972	15	
	4	515	1973	14	
Pickering B	5	516	1983	4	
	6	516	1984	3	
	7	516	1985	2	
	8	516	1986	1	
Bruce A	1	759	1977	10	
	2	769	1977	10	
	3	759	1978	9	
	4	769	1979	8	
Bruce B	5	835	1985	2	
	6	837	1984	3	
	7	837	1986	1	
	8	837	1987	<1	
HYDRO QUÉBEC					
Gentilly 1	Single	250	-	N/A	Prototype CANDU-BLW Full power 1972 Decommissioned 1984
Gentilly 2	Single	630	1983	4	
NEW BRUNSWICK POWER					
Pt. Lepreau	Single	630	1983	4	

Preventive maintenance programs are plant specific, but are based on the same general principles, manufacturers' recommendations, warranty and regulatory requirements, and accumulated experience. Canadian Quality Assurance Standard CSA N286.5 requires that the programs are periodically reviewed and revised to achieve the required level of equipment performance.

Preventive maintenance programs include inspection, testing, surveillance, repair, and replacement activities designed to minimize the frequency and consequences of system and component failures. These activities are used to a greater extent in maintaining the required level of performance of safety equipment than process equipment. They are also the primary means of detection and mitigation of aging and service wear effects in NPP components.

An example of a preventive maintenance program development, focused on process equipment, is the program review which was initiated in 1985 by Ontario Hydro's Central Nuclear Services and the station staff at Bruce A nuclear generating station[1]. It included four separate tasks, described below.

a) A review of preventive maintenance practices of selected key equipment was performed to increase reliability and reduce costs and radiation dose.

   Forty major items of equipment that required excessive maintenance were selected for the review. The selection was based on information from the utility cost (direct maintenance and outage costs) and reliability data bases and on interviews with the maintenance staff, who confirmed items that required excessive maintenance.

   The review of the selected equipment included collection of maintenance data (over the past three years), analysis of the data to identify critical components (i.e., those which required frequent maintenance and/or resulted in high maintenance and/or outage costs), and evaluation of improvement options. Unnecessary work was eliminated (e.g., call-ups when there is control room indication of equipment condition) and new preventive maintenance introduced to reduce breakdown maintenance. These changes resulted in improved equipment reliability, averaged saving of Canadian $8000/a per item reviewed, and, in some cases, radiation dose reduction.

b) An implementation of a modern vibration monitoring system was carried out to diagnose problems before equipment breakdowns.

Vibration monitoring is a powerful technique capable of detecting deterioration of rotating components (e.g., bearings, couplings, and impellers). In the past, its usefulness was limited by the complexity of vibration measurements, data analysis, and interpretation which had to be performed by specialists. Modern techniques and instruments, such as Fast Fourier Transform, portable recorders, and microcomputers, enabled development of a vibration monitoring system which could be used by maintenance staff for equipment condition monitoring and maintenance scheduling. Installation of the new system was completed in April 1987. During the first year of its use Ontario Hydro Research will provide training and technical support to the station staff.

c) A review of maintenance of the station heat exchangers was performed to prevent failures.

Station heat exchangers perform functions of various degrees of production and/or safety significance. All of them suffer from time dependent degradation which has different consequences depending on the heat exchanger application and the specific problem. The review of maintenance of station heat exchangers was carried out to improve detection and mitigation of the aging effects. It included an examination of materials of construction, water chemistry, flow conditions, thermal duty, failure modes, and consequences of failure. The review resulted in revised maintenance strategy as well as recommendations for design and operational changes intended to minimize flow induced vibration of the bleed cooler (a part of the heat transport inventory control system) and to eliminate stagnant water conditions which lead to an aerobic attack of bacteria on copper based alloys used in some heat exchanger tubing. The revised preventive maintenance of heat exchangers includes periodic inspections using visual, eddy current, and vibroacoustics methods, periodic cleaning using mechanical brushing, chemical cleaning techniques or a combination of these techniques. The predicted cost saving during the remaining station life is $2.8 million.

d) A review of existing equipment maintenance records and design of a computerized maintenance history records system was done to enable development of a predictive maintenance program whose objective is to prevent failures by doing the correct amount of maintenance.

The program implementation requires collection and analysis of large quantities of data on equipment maintenance histories to permit tracking of equipment conditions. An

equipment maintenance history records system was, therefore, developed to serve the foregoing purpose. The system includes information on preventive and breakdown maintenance work, operating data, and pertinent performance standards. It uses interlinked microcomputers to store and analyze the data and report trends. As a first step, the program includes heat exchanger monitoring to detect and measure tube deterioration, an improved vibration monitoring of rotating equipment, and monitoring of key valves in the steam and feedwater service to reduce steam (i.e., heat) losses from the power production cycle.

2.2 Significant Event Reporting System

The second major component of the operational safety management program is the Significant Event Reporting system, whose purpose is to control and limit the risk associated with NPP operation.

This is accomplished through systematic detection, analysis and correction of deficiencies, including those caused by aging degradation. Ontario Hydro SER system has the following important features.

a) Significant Event Reports are prepared for abnormal or unscheduled events that may have a detrimental effect on worker or public safety, environmental protection, production reliability and cost;

b) equipment and operation deficiencies are recorded in a specified, systematic manner to allow event review and analysis;

c) a multi level diverse screening process includes reviews by plant staff and management, different head office groups, a senior management review committee (when needed), and the regulatory staff;

d) trends of equipment and system deficiencies, indentified by the SERs, and their causes are monitored; and

e) lessons learned from SERs are communicated to other CANDU stations, owners, designers, and equipment manufacturers.

Selected SER information (event summary, cause and consequence codes, various station, system and equipment codes, status of follow-up actions) is entered into SERBASE - a data base used to store and monitor trends of equipment and system faults and their causes. A review of the Pickering A NPP SERs using SERBASE showed that since 1976 (36 reactor years) out of a

total of almost 2000 SERs issued, 150 were classified as being caused by equipment wear-out, and 95 by equipment calibration drift (some of which was likely due to aging).

The above numbers do not indicate fully the extent of significant events caused by aging and service wear effects because the SER classification by cause does not include "aging" as a possible cause and therefore it may be hidden under other codes such as "random or not known". Also it is current practice not to change the originally entered SER cause code, even if the follow-up investigation identified a different cause. Other data relevant to evaluation of aging effects such as equipment age, service life and environment, are not available from SERBASE.

Despite the above shortcomings, the SER system has been quite effective in detecting and correcting aging and service wear related failures. For example, in 1982 a series of failures of dousing system solenoid valves located in the boiler room at Douglas Point NPP was identified by the SER system. Although originally classified as random or unknown cause failures, the follow-up investigation showed aging degradation of elastomeric components of the valves to be the cause of failures. Long term exposure to atmospheric temperature of about 70°C was the major contributing factor to the elastomeric component degradation. The boiler room design temperature of 40°C had increased over a few previous years, primarily due to insulation deterioration on high temperature components. Corrective actions included installation and periodic replacement of new high temperature kits in the solenoid valves, repair of deteriorated insulation and reducing the air conditioning unit temperature set point. Although the boiler room temperature was not much reduced, the failure rate of the solenoid valves decreased. Other plants were directed by the utility to review the Douglas Point experience and take steps to reduce higher than normal boiler room temperatures.

2.3 Reliability Based Assessment of Performance of Safety Related Systems

Performance of safety related systems is monitored on an ongoing basis and formally documented in the Quarterly Technical Reports (QTR). The four QTRs comprise the annual report on NPP operation and maintenance which must be submitted by the licensee to the AECB as one of the conditions of an NPP operating licence. The final QTR of the calendar year is of an expanded form which includes a quantitative assessment of the year's performance as a whole.

The performance is measured against standards or targets which are established by the utilities on the basis of regulatory requirements, internal and external experience, international

recommendations and other considerations. The fundamental reliability targets are:

- frequency of serious process failures to be less than one per three years;

- unavailability of each special safety system (shutdown, emergency core cooling and containment) to be less than 10^{-3} a/a.

("Serious process system failure" means a failure of a process system which could, in the absence of special safety systems action, lead to significant fuel failures or significant radioactive release at the station boundary.) If a performance target is exceeded, the causes (e.g., aging degradation) are identified along with corrective and follow-up actions which may include changes to testing, inspection and monitoring practices (e.g., frequency, and parameters monitored), review and possible changes of design, operating and maintenance practices, and R&D work.

For poised systems, that is, systems which are normally inactive and are triggered on demand, a test program is developed and implemented to provide confidence that the system would work when needed. Components or functions to be tested and the test frequency are determined using reliability analysis and adjusted on the basis of in-service experience.

Reliability surveillance groups at NPPs monitor daily test records, control room logs, work reports and deficiency reports to ensure that all reactor safety deficiencies are properly recorded, classified as to their severity, and corrected. Component faults are classified in terms of their effect on the following two criteria:

a) Active safety related systems should always operate in such a way that fuel temperatures remain within well defined limits; and

b) poised safety related systems should always be ready to operate according to their design intent.

To assess performance of poised safety related systems several reliability indicators are evaluated and monitored, including system actual inoperability and system actual and expected unavailabilities. (Inoperability is synonymous with the total incapability of a system, while unavailability reflects its impairment - the system is unable to satisfy all design requirements, but a significant benefit would still be obtained

from its operation. When a system is "inoperable" it is also "unavailable", but not necessarily vice versa. For more details, see Ref. 2.) The actual system inoperability and unavailability are direct measurements of the time a system is impaired in a year. Expected system unavailability, calculated using constant failure rate reliability models and taking into account all relevant fault data and corrective actions over the life of the plant, is the indicator of future system performance. By monitoring the trend of the expected system unavailability and individual component failure rates, it is possible to identify deteriorating performance before it is manifested as actual system unavailability. Analysis of such performance is done to determine the causes, possibly aging degradation, and appropriate corrective action. (The component failure rate monitoring program annually evaluates component failure rates and compares them against component lifetime experience and generic failure rate data.)

Monitoring and assessing performance of active safety related systems (i.e., process systems) involves recording and trending of both actual and near-miss serious process failures. Should either of these trends indicate a potential problem, a more detailed review of all component faults of a system is carried out to determine major contributors to undesirable performance and appropriate follow-up actions.

An example of an aging degradation problem, which was identified through the reliability based assessment of performance of safety related systems, was the degradation of grease used on limit switch assemblies of the Bruce A emergency core injection (ECI) system. In 1978, the assessment revealed that the failures of limit switches of the injection valve actuators were one of the major contributors to the ECI system exceeding its unavailability target. The cause of many of the limit switch failures was determined to be the degradation of grease used to lubricate the limit switches. In the high temperature and radiation environment the grease turned into a hard "varnish" preventing limit switch, and consequently injection valve, operation. This problem almost completely disappeared after a change was made to the type of grease and an improved vault ventilation reduced the ambient temperature from 100°C to the 50-60°C range.

3. REGULATORY REVIEWS

The Directorate of Reactor Regulation of the Atomic Energy Control Board is responsible for the regulation of nuclear power plants in Canada. The Directorate's two Power Reactor Divisions have project officers stationed at each of the commercial NPPs in Canada to carry out ongoing reviews, inspections and assessments

of plant operation and maintenance, including reviews of the discussed operational safety management program. Specialist technical support is provided by the AECB Head Office staff.

Preventive maintenance programs are audited periodically by AECB quality assurance specialists, together with the project officers and other relevant specialists (e.g., in radiation protection or instrumentation and control) to ensure that they are carried out in accordance with approved procedures. (The procedures must meet the requirements of governing standards.) On the basis of deficiencies found, recommendations and directives are issued to the licensee to make necessary improvements. Program effectiveness in achieving the required level of equipment performance is being assessed on a continuous basis by the AECB project officers through routine inspections and monitoring of internal station documentation. Minor deficiencies are discussed informally with the station staff, while more significant ones are recorded formally on a list as outstanding action items. These items are discussed with the station management and removed from the list only after a satisfactory correction has been implemented.

Significant Event Reports issued at an NPP are reviewed by:

a) the project officers to determine an event's safety significance, to identify any chronic problems and to check the adequacy of the remedial actions taken and planned;

b) a special Head Office Review Group to identify any unhealthy failure or error trends, to assess the effectiveness of corrective actions, and to inform project officers and AECB management of its conclusions; in addition the international community is informed of any relevant major events through the Nuclear Energy Agency of the OECD and the IAEA.

The AECB review is independent of and additional to that done by licensees to ensure that appropriate corrective actions are taken to prevent or minimize recurrence and consequences of the experienced events.

For example, the regulatory reviews of the licensee's analyses of a problem at both Pickering A and Bruce A reactors with pressure tube cracks near rolled joints, of a rupture of a Zircaloy-2 pressure tube at Pickering Unit 2, and of the solutions proposed by the licensee resulted in a mutually agreed series of corrective actions. These actions were aimed at preventing or minimizing the failures, a significantly expanded inspection program intended to detect pressure tube degradation

before failure, and a more intensive R&D program to develop better inspection techniques, better fuel channel design as well as better understanding of the degradation processes.

In its review of safety related systems performance, which is documented and assessed in the Quarterly Technical Reports, AECB staff checks both the numerical results (i.e., various reliability parameters monitored) and the supporting information from which the results are derived.

The supporting information is reviewed to get a more complete picture of the system performance, and to ensure that the results are correctly derived. In this review AECB is interested in the following:

- complete entries in the fault tables
- proper classification of the faults
- proper duration of the poised system faults (failure mode determines if we are dealing with a time based or demand based failure and thus determines the appropriate failure duration)
- causes of the faults (what is the basis for the identified cause(s), are there any other likely causes?)
- proper corrective actions (will they eliminate or minimize the identified cause(s) and thus reduce the fault probability?)
- trends of component and system failure rates and unavailabilities (e.g., does an increasing failure rate indicate wear-out stage or common cause failures due to changed service conditions?)
- correctness of the system reliability models (e.g., are system modifications correctly modelled?)
- correctness of the reliability data used in the predictions (e.g., is all relevant data taken into account?)
- correctness of the calculations.

Conclusions are drawn from the above described review as to whether the performance of the safety related systems can be accepted as satisfactory, or if improvements are required. This is one of the main items on the agenda of an annual review meeting with the licensee. For example, the substandard performance of the Bruce A emergency core injection system mentioned above in Section 2.3 was the subject of discussion at the annual plant performance review meeting with the station management. Subsequently, the AECB raised the subject with the utility management noting agreement with the initiated corrective actions, but requiring the utility to expedite the actions to improve the ECI system availability.

4. PRESENT AND FUTURE DEVELOPMENTS

The operational safety management program, whose application to the detection and mitigation of aging effects was outlined in Section 2, was first introduced at the CANDU demonstration plant NPD 25 years ago. It has been under continuous development, incorporating lessons learned and new knowledge. The program has served us well, and its development will continue.

While in the past aging was considered just one of many possible causes of component failures, and aging related research as well as design, operation, monitoring and maintenance improvements have been primarily in response to experienced operational problems or failures, both the industry and the AECB have started to consider effects of aging on plant safety in a more deliberate way. Some of the recent examples include the above mentioned predictive maintenance program development at Bruce A NPP, the Pick-Up (Pickering Upgrade) Inspection Program during Zircaloy-2 pressure tubes replacement at Pickering NPP Units 1 and 2 (the objective was to determine the condition of 70 major component types susceptible to aging degradation, to upgrade deteriorated components and/or to develop an optimum inspection and maintenance strategy for the future), and several research projects.

Discussions with the industry have been held both on a formal and informal level. These are intended to lead to a more systematic approach to NPP aging issues. There is a need to continue reviews of current monitoring, testing and inspection methods to ensure that appropriate time variant parameters (capable of revealing aging degradation before functional capability is lost) are monitored, as well as reviews of the effectiveness of existing maintenance methods in mitigating aging effects.

In addition, there is a need for greater understanding of various mechanisms and stressors causing time dependent degradation of safety related plant components; and of the effects of aging degradation on component and system reliability and, therefore, plant safety. Because of the large number of different NPP components, the variety of their applications, the complexity of aging processes and limited knowledge, we are looking forward to further and expanded cooperation, both on a national and an international level.

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ACKNOWLEDGEMENT

The author wishes to thank J.W. Beare and J.S.C. Tong of the AECB and B.D. MacTavish of Ontario Hydro for helpful comments and suggestions.